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Testing of a Catalytic Partial Oxidation Diesel Reformer with a Solid Oxide Fuel Cell System

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Introduction

Rural Alaska currently uses diesel generator sets to produce much of its power. The high energy content of diesel (i.e. ~140,000 BTU per gallon) makes it the fuel of choice because this reduces the volume of fuel that must be transported, stored, and consumed in generating the power. There is an existing investment in infrastructure for the distribution and use of diesel fuel. Problems do exist, however, in that diesel generators are not very efficient in their use of diesel, maintenance levels can be rather high as systems age, and the environmental issues related to present diesel generators are of concern.

The Arctic Energy Technology Development Laboratory at the University of Alaska – Fairbanks sponsored a project to address the issues mentioned above. The project integrated two successful systems, a diesel reformer and a tubular solid oxide fuel cell unit, and tested those systems with the objective of producing data for design of a for-purpose diesel fueled solid oxide fuel cell system that would be deployed in rural Alaska. The reformer converted the diesel to a mixture of carbon monoxide and hydrogen that could be used as a fuel by the fuel cell. The high temperature nature of the solid oxide fuel cell (SOFC) allows the system to directly use this mixture to generate electricity and provide usable heat with higher efficiency and lower emissions. The high temperature nature of the SOFC is more compatible with the arctic climate than are low temperature technologies such as proton exchange membrane fuel cells.

This experiment used a SOFC system that was designed to internally reform methane and a catalytic partial oxidation (CPOX) diesel reformer. The diesel reformer produces a reformat mixture that is approximately 140 BTU per scf (after removal of much of the reformat water) as compared to a methane based reformat that is over twice that value in BTU content. The project also considered the effect of altitude since the test location will be at 4800 feet with the consequential drop in oxygen content and necessary increases in flow rates.

Importance to Alaska

Electric generation in Alaska is characterized by small utilities which service non-urban areas where the average village population is about 450 people. Many villages are only accessible by aircraft and the transportation costs of fuel for power generation can become significant. Over 90% of the diesel fuel

used in Alaska is used for power generation. The efficiencies of the plants typically range from about 17% to 30+ % dependent on the size, speed (*note: slower speed diesel systems are generally more expensive but are more efficient*), and age of the diesel generation unit. As the diesel generation sets become older, the amount of maintenance increases. Fuel cells become an attractive alternative when the overall costs are considered (i.e. cost per kWh exceeds \$.40 in some remote locations). Fuel cells have the potential to cut the amount of diesel used by at least 50% and thus significantly reduce the amount of fuel that must be transported. The high temperature nature of the SOFC system also generates high quality heat that can be used to further improve fuel utilization.

An example of the impact of going to a higher efficiency fuel cell system could be seen by considering a village with three (3) thirty-five kW generators running for power. Even using a newer conventional system with an efficiency of 25%, the units would require about 1800 pounds of fuel per day if run at full capacity. A 50% efficient SOFC system would use half that amount of fuel cutting transportation, cost of fuel, storage cost, and environmental impacts. Taking a typical fuel cost in a remote village (i.e. \$4/gallon delivered – *Arctic Rural Energy Conference, 2004*), a typical load profile, and the using 100 kWe as the peak load it is possible to generate Table 1 (see Attachment 1 for calculation).

Table 1
Comparison of Operating Cost
Diesel Generator versus SOFC
Comparison for One Year

System Type	Efficiency	Fuel Used	Cost per Year
Diesel	25%	~49,000 gal	\$194,000
SOFC	50%	~24,000 gal	\$97,000

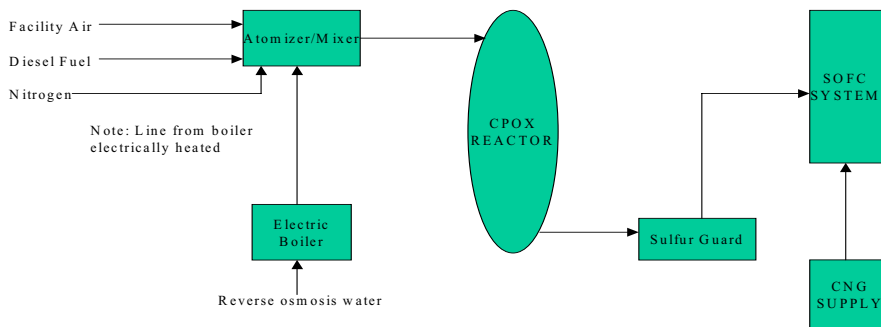
Note: No cost included for transportation, storage, maintenance, et al

It can be seen that even for small power generation systems, the savings can be substantial over the period of a year. When reductions in transportation, storage, and maintenance are considered, the savings are even larger. Storage of the fuel must consider the likely scenario that access will not be possible during certain periods of the year. Storage must also consider the harsh climate and potential environmental impact. Any method that can improve fuel utilization (i.e. reduce transportation requirements), reduce the storage requirements, reduce the required maintenance, and improve the environmental aspects of the emissions is of great interest. Of course, the relatively hostile operating environment requires that any system must be proven reliable, simple to operate and repair, and robust.

Reforming system

The first portion of the system that was tested is a catalytic partial oxidation (CPOX) diesel reformer that was designed, constructed, and assembled by SOFCo-EFS. SOFCO is a subsidiary of BWX Technologies that is located in Alliance, Ohio. SOFCO has been producing heavy hydrocarbon reformers since the mid-1990's. Most recently they worked with the Idaho National Laboratory (INL) to design, construct, assemble, and test a 500 kWe high sulfur diesel (fuel specification NATO F-76) for Office of Naval Research. SOFCO provided the basic CPOX equipment to INL. The INL was responsible for providing the fuel, a nitrogen purge system, an electric boiler that could provide any needed steam, reverse osmosis water for the boiler, compressed air, a water removal system, compressed natural gas for initial startup of the SOFC, a sulfur guard bed, and valves to connect the foregoing items. The system was generally in the configuration noted in Figure 1 below.

Figure 1
Block Diagram of CPOX System



The CPOX reactor was attractive because of its relatively compact size compared to other alternatives and its reduced demands for water (as compared to steam reforming or autothermal reformers). The high activity of the CPOX unit results in space velocities that are an order of magnitude higher than those with autothermal reforming. The potential exists to conduct anode recycle from the SOFC system and reduce the water demands to a very low amount. Information from SOFCO's diesel and methane reforming experiments conducted prior to the experiment is shown in Table 2 below.

TABLE 2
RESULTS OF DIESEL AND METHANE REFORMING

	<i>Methane</i>	<i>Low Sulfur</i>	<i>Synthetic</i>
Hydrogen %	31%	30%	33%
Carbon Monoxide %	14.6%	12.4%	12%
Fuel type	Natural gas	Phillips	Syntroleum
Hours tested	2000+	4	4
Hydrocarbon Conversion	93%	99%	99%
Reformer efficiency	77%	82%	80%

Note: H₂ and CO shown in Table 2 are mole percentages on a dry basis. Data reported from SOFCO-EFS tests.

The CPOX reactor was designed to operate on low sulfur diesel and provide a reformat stream suitable for a solid oxide fuel cell system. Preliminary tests indicated that the reformer will provide 150 SLPM at 800^o C on a dry basis, 2-4 psig. Prior to water removal, the reformat had about 20% water content and the above percentages would need to be modified if measured on a wet basis. The system operated basically without steam for the reformation operation when operating with methane. For the diesel fuel some steam was required to maintain coke free operation and hydrogen percentages reflect the generation of hydrogen from that steam.

Water coming to the system was prepared by running normal city water through a reverse osmosis system to remove impurities. The boiler provided steam to a mass flow controller that can provide steam of up to 5.8 pounds per hour at 500^o C within 10% accuracy. The line between the flow control valve and the atomizer was heat traced with electric heat tape to maintain temperature. Facility air was put through a pressure regulator, an air filter, a mass flow controller, and then an air heater prior to entering the atomizer of the reformer. The diesel was pumped through a pressure regulator, a fuel filter, and a mass flowmeter to the atomizer.

Exiting the CPOX reactor, the reformat is cooled to approximately 600^o F prior to entering the sulfur guard bed. The reformat is then cooled in a heat exchanger and enters a water removal device. A flowmeter controls the amount of reformat entering the SOFC. The delivery conditions of the reformat are .25 - .5 psig and 120^o F maximum temperature.

Solid Oxide Fuel Cell System

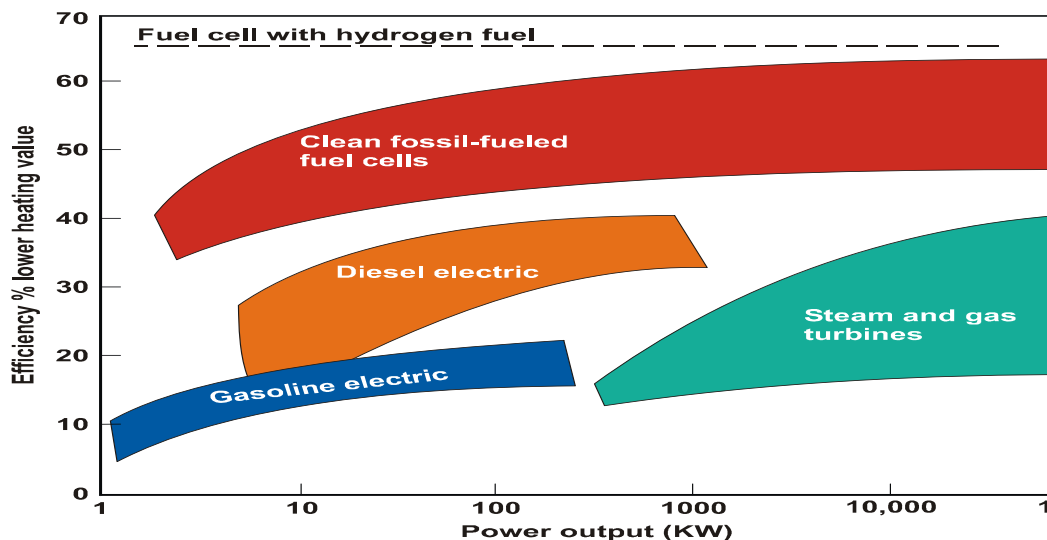
The other main portion of the system test was the SOFC system. It was rated at 5 kWe operating on reformed natural gas at sea level. The SOFC system was designed and assembled by Acumentrics Corporation. The system was based on Acumentrics proprietary high temperature tubular SOFC technology

that operates at approximately 750° C. The unit was designed to internally reform natural gas or other low chain hydrocarbons. The unit was approximately 68" long, 36" wide, and 60" high and weighs about 1200 pounds. The SOFC system was in a NEMA 3R enclosure with removable locking doors and was constructed to withstand temperatures from 20° F to 120° F.

The SOFC was brought on line with a purge gas of hydrogen and argon. No fuel reformer was needed when operating on natural gas because the temperature and materials of the system act to internally reform the fuel. The reformat generated by natural gas has a higher BTU content per cubic foot than that generated from diesel fuel. This is because of the higher weight percentage of hydrogen in methane as compared to diesel. The reaction of the system to the lower reformat BTU content and the effect of the heat management required when the endothermic reforming reaction occurred external to the fuel cells was of critical interest.

As previously mentioned, the SOFC system was of particular interest to Alaska because of the high temperature nature of its operation (i.e. greater compatibility with the Alaskan environment than low temperature cells). The efficiency of fuel cells as compared to other methods of power generation is shown in Figure 2 below.

Figure 2
Comparison of Power System Efficiency



Note: Figure 2 is from DOE presentation on fuel cells, 1997

The unit was tested at the Acumentrics facility in Massachusetts on pipeline natural gas. The unit was then shipped to INL and initially tested on

compressed natural gas (CNG). Since INL is at 4800' altitude, this initial test characterized the variation in performance that was generated by the change in altitude. The variations in performance attributable to the change in the partial pressure of oxygen, atmospheric pressure, and other environmental conditions were observed while operating on CNG as a fuel.

After the initial tests on natural gas, the unit was switched to operation on diesel reformat. The operation of the unit was closely monitored and data recorded regarding the response of the unit to the lower BTU content of the diesel reformat. The data recorded will be used to design a for-purpose integrated system that would be deployed in rural Alaska. Testing of the system commenced March 15, 2005. Preliminary results on the testing of the linked system are shown in Table 3 below.

**TABLE 3
PRELIMINARY SYSTEM RESULTS**

<i>Fuel Type</i>	<i>Hydrogen</i>	<i>Carbon Monoxide</i>	<i>CH₄ - C₃H₈ ppmv</i>	<i>Load</i>
Synthetic Diesel	20%	18%	987	2.5 kW
Low Sulfur Diesel	16%	15%	657	2.5 kW

Notes: 1. Amounts shown are on a dry basis
 2. Samples were drawn and had oxygen contamination, amounts are corrected.
 3. Some drift on steam flow between samples may have affected the numbers.
 4. System efficiency was about what was expected for a non-optimized system.
 5. Percentages reflect the use of some steam in the reforming process

Summary

A SOFC system manufactured by Acumentrics was tested with a CPOX diesel reformer provided by SOFCO-EFS under a project sponsored by UAF-AETDL. Each system was previously tested independently with acceptable results. The SOFC was initially benchmarked at INL on natural gas to test the effect of the altitude change and then the unit was tested on the output of the CPOX reformer. The data from the test at INL will be used to design a for-purpose SOFC system that will be deployed into Alaska. The objective is to provide fuel cell based power generation for remote locations while taking advantage of existing fuel distribution infrastructure.

Preliminary results indicate that the CPOX reformer can successfully operate on either low sulfur diesel or synthetic diesel, albeit that some steam was required for sustained operation. The operation of the reformer appeared to be more stable on the synthetic diesel. The volume of reformat gas fed to the

SOFC was increased over the volume of CNG to account for the lower BTU content of the reformat. The SOFC system needed adjustments in cooling air when operated on the reformat. The SOFC started to climb in temperature when the reformat gas was introduced. It appeared that the cooling effect of the endothermic reaction of reforming natural gas on the cells was greater than the cooling provided by the increased volume of the reformat. Thus, the volume of cooling air to the SOFC stacks had to be increased. With the cooling air adjustments, the SOFC operated in a stable manner and successfully operated on the reformat.

ATTACHMENT 1

PARAMETERS:

1. Three (3) 35 kW diesel generators
2. Efficiency of the units @ 25%
3. No recovery of heat
4. BTU content of one (1) gallon of diesel ~128000 BTU
5. Heat rate to generate one (1) kW @ 100 % efficiency ~3414 BTU
6. Cost of fuel delivered @ \$4 per gallon
7. Average load over the year is 50% of capacity

CALCULATIONS:

kWh per year

$$105 \text{ kW} * 24 \text{ hours/day} * 365 \text{ days/year} * 50\% \text{ (load factor)} \approx 460,000 \text{ kWh/year}$$

BTU use @ 25% efficiency

$$3414 \text{ BTU/kWh} * 100\%/25\% \approx 13650 \text{ BTU/kWh}$$

BTU use per year

$$460000 \text{ kWh/year} * 13650 \text{ BTU/kWh} \approx 6.3 \times 10^9 \text{ BTU/yr}$$

Gallons of fuel per year

$$6.3 \times 10^9 \text{ BTU/yr} * 1 \text{ gallon diesel/128000 BTU} \approx 49000 \text{ gallons}$$